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ICE DRIFT IN THE WEDDELL SEA

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COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
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Factors determining ice drift in the Weddell Sea are analyzed mathematically on the basis of observations made along Siberia and modified to fit local hydrographic conditions. Data are tabulated and graphed on the relation between ice drift and wind with constant wind conditions and increasing ice resistance, surface-drift velocity and friction depth assuming ice resistance to be proportional to the square of the surface velocity, seasonal variations in the wind factor and deviation angle, seasonal variations in the coefficients

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of ice resistance and wind action, and the relation between wind and ice drift under quasi-stationary conditions. Ice drift in the Weddell Sea is determined by wind action on the ice, the resistance of ice against ice, the depth of the friction layer in the water, and the deflecting force of the earth's rotation. The importance of the wind factor in the Weddell Sea is greater than in the open Arctic Ocean since the ice offers a greater surface to the wind.

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I. Introduction

Brennecke [1], processing wind and drift observations made by the German Antarctic Expedition aboard Deutschland in 1911-1912, showed that surface motion in the Weddell Sea was caused only by wind; that is, that ice drift in the Weddell Sea was pure wind drift. Brennecke also showed that this ice drift could not be reconcilced with Ekman's theory of drift currents in the ocean. This theory states that in the southern hemisphere a pure surface drift current drifts 45° to the left of the wind direction, independent of current speed. Brennecke finds, however, that this angle of deflection is a mean of only 34°, and demonstrates that the deflection decreases with increase in current speed, as well as during winter and spring. Relative drift speed, for which H. Thorade [2] introduced the term "wind factor," remains constant, but has an extraordinarily high value. Brennecke and Thorade base nonconformance with Ekman's theory on the difference between the ice drift and the ocean current, without, however, detailing this difference.

Ekman's theory [2], which is based on Nansen's [4] considerations, in turn is based on the premise that wind currents in the ocean are determined by three forces: (1) the tangential force of the surface wind, acting in the direction of the wind; (2) the force produced by the increased internal friction resulting from turbulence; and (3) the deflecting force of the earth's rotation.

However, this simple premise does not seem to be adequate for ice drift. Even Nansen, in his work with wind and drift observations made by the 1893-1896 Fram expedition, pointed out that the resistance produced by ice colliding with ice in another state of motion, cannot be overlooked. He indicated that the small deflection angle (27°) he observed, could be ascribed to the effect of

this resistance. Brennecke too mentions this form of resistance, particularly in his introduction, and further that ice resistance increases greatly in the winter. He emphasizes the fact that ice resistance is the result of wind field limitations. The area over which wind always blows with equal force is relatively small, so ice in adjacent areas moves differently, and ice heads form at wind boundaries, or the ice breaks open and polynyas are formed. The latter are quickly covered by new ice in the winter, and a continuous ice cover is again formed. The appearance of drift ice, the piled-up remains of ice floes, the numerous ice ridges, etc., are evidence of the fact that the kinetic energy of ice in motion is constantly being destroyed, that is, that motion is subject to resistance created by ice colliding with ice.

The author, based on observations from the Maud expedition [5], was able to show that ice resistance is a decisive factor in the ice drift on the Siberian continental shelf, where what is seen is pure wind drift, determined by three forces: (1) a force that represents the effect of the wind, and acts in the same direction as the wind, the scalar value of which is proportional to wind speed; (2) a resistance opposing ice motion, the scalar value of which is proportional to drift speed; and (3) the deflecting force of the earth's rotation. The proportionality factor with which wind speed had to be multiplied to obtain wind force, was termed "wind action" for reasons of brevity. It was found that wind action was dependent on the turbulence of the bottom layer of the atmosphere. The resistance factor was dependent on ice conditions. The factor was small when polynyas were present; the factor was large when the ice was densely compacted. Many of the observations that involved the relationship between wind and drift thus were readily explained by this simple principle.

We were interested in finding out if the observations that had proven to be so valuable to an understanding of ice drift on the Siberian continental shelf could be applied to ice drift in deep ocean waters. But the observations made by the Fram expedition are not suited to this kind of study, because in the deep Arctic Ocean there is an ice drift caused by a permanent surface current, as well as a wind drift. The effect of this permanent current would have to be eliminated in each case in order to study pure wind drift, and the wind drift values thus obtained would be subject to large errors because constancy of the permanent current would have to be assumed in the elimination, something that is beyond the realm of probability. Brennecke's Weddell Sea observations, however, are excellently suited for a study of the type indicated because this sea has no demonstrated permanent current.

Weddell Sea ice drift cannot be treated in the same manner as drift on the Siberian continental shelf because hydrographic conditions in the two areas are very different. There is marked layering of the water on the Siberian continental shelf. The surface layer is relatively light, and is separated from the heavy bottom layer by a sharp thermocline. Vertical equilibrium in the surface layer is virtually nonexistent for the greater part of the year, so turbulence in this layer must be very high. On the other hand, turbulence within the thermocline, which is remarkably stable, must be so slight that this layer is in the nature of a sliding plane. The surface layer is, for the most part, carried along in the direction of surface motion because of this layering, and this motion is not transmitted to the bottom layer. Internal friction is not

pertinent to surface motion under these conditions, so one is justified in regarding ice as an elastic plate. Resistance to the motion occurs because this plate is being compressed by changing winds. Hydrographic conditions are entirely different in the Weddell Sea, however. There is no thermocline a short distance from the surface; density increases slowly, and evenly, with increase in depth. Correspondingly, Brennecke demonstrated that change in wind current with depth is in agreement with Ekman's theory. The current drifts to the left with increase in depth, and current speed decreases. Brennecke found 50 m to be the mean for the depth of frictional resistance. The effect of internal friction, as well as the effect of ice resistance, therefore must be taken into consideration in the Weddell Sea, and theoretically this is readily accomplished under simple conditions.

II. Ice Drift Theory

If it is assumed that water motion is solely the result of frictional forces, and that the motion of the water particles is not accelerated, then the motion equations for the southern hemisphere are

$$\left.\begin{aligned} \mu \frac{\partial^2 w_x}{\partial z^2} - 2\omega \sin\varphi\, w_y = 0 \\ \mu \frac{\partial^2 w_y}{\partial z^2} + 2\omega \sin\varphi\, w_x = 0 \end{aligned}\right\} \qquad (1)$$

where

x, y, z are the rectangular coordinates, with z positive downward;

w is water speed;

μ is the coefficient of virtual internal friction, assumed to be independent of depth;

ω is the angular velocity of the earth;

φ is the geographic latitude, assumed to be constant in the area under consideration.

An integral of these equations is

$$\left.\begin{aligned} w_x = A_1 e^{-\beta(1+i)z} + A_2 e^{-\beta(1-i)z} + A_3 e^{\beta(1+i)z} + A_4 e^{\beta(1-i)z} \\ w_y = iA_1 e^{-\beta(1+i)z} - iA_2 e^{-\beta(1-i)z} + iA_3 e^{\beta(1+i)z} - iA_4 e^{\beta(1-i)z} \end{aligned}\right\} \qquad (2)$$

$$\beta = \sqrt{\frac{\omega \sin\varphi}{\mu}},$$

where A_1, A_2, A_3, and A_4 are integration constants, to be determined from interface conditions. Let us introduce

$$z \to \infty, \quad w_x = w_y = 0, \qquad (3)$$

as the interface conditions; that is, in concordance with Brennecke's results, we assume that wind current disappears at great depth. This condition yields

$$A_3 = A_4 = 0.$$

Let us put

$$z=0\left\{\begin{aligned}\mu\frac{\partial w_x}{\partial z}&=f(w)w_x\\ \mu\frac{\partial w_y}{\partial z}&=-F(v)\cdot v+f(w)w_y\end{aligned}\right. \tag{4}$$

for the upper interface condition. Here v is wind speed, and $f(w)$ and $F(v)$ are two unknown functions. The coordinate system is oriented such that the wind direction is positive along the y-axis. Setting $f(w) = 0$, and $F(v)v = T$, where T is the tangential force of the wind, we obtain the interface condition introduced by Ekman. These equations express the premise that tension in a direction opposite to the surface motion must be taken into consideration at the upper interface along with the tensions produced by wind and internal friction. This tension expresses the resistance produced by ice colliding with ice.

Constants A_1 and A_2 are readily found by using the conditions in Eq. (4). But we are interested only in surface motion, so

$$z = 0,\ w_x = A_1 + A_2,\ w_y = i(A_1 - A_2).$$

Eqs. (3) and (4) yield

$$\left.\begin{aligned}(f(w)+\beta\mu)w_x-\beta\mu w_y&=0\\ \beta\mu w_x+(f(w)+\beta\mu)w_y&=-F(v)v\end{aligned}\right\} \tag{5}$$

The deflection angle, α, is given by the equation $\tan\alpha = w_x/w_y$, because deflection is to the left. Using the first of Eqs. (5) we find

$$\operatorname{tg}\alpha=\frac{\beta\mu}{\beta\mu+f(w)}=\frac{D\omega\sin\varphi}{D\omega\sin\varphi+\pi f(w)}, \tag{6}$$

where D is the depth of frictional resistance introduced by Ekman. It is obvious that the deflection angle is 45° when ice resistance is zero, and that the angle decreases with increase in ice resistance.

The wind factor, from Eqs. (5), is

$$r=\frac{w}{v}=\frac{\pi}{D\omega\sin\varphi}F(v)\sin\alpha, \tag{7}$$

that is, the wind factor decreases with increase in ice resistance, all other conditions being equal, because the deflection angle decreases with increase in resistance. The relationship between wind factor and deflection angle therefore is such that the termini of the relative drift vectors, plotted from the origin of the wind vector, are on a circle. The center of the circle is in the normal plotted to the left of the wind direction, at distance $\pi F(v)/2D\,\omega\sin\varphi$ from the origin of the wind vector. Figure 1 illustrates this relationship.

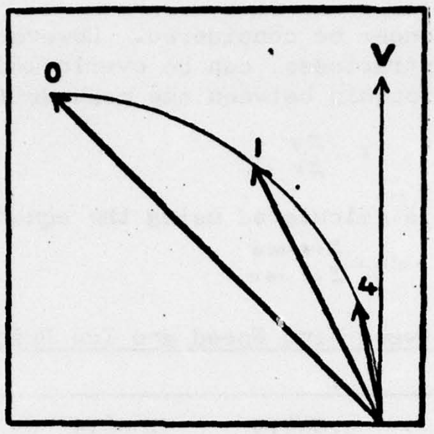

Figure 1. Theoretical relationship between wind and ice drift when wind effect is constant and ice resistance is increasing.

What must be emphasized here is that f(w) and F(v), introduced here, cannot be identified with the coefficients k and c introduced in the work with the observations made by the Maud expedition. The magnitudes have a different physical meaning because of the entirely different manner in which the subject under consideration was viewed. Moreover, the dimensions are different. The two functions are, however, related to the coefficients mentioned, so it can be anticipated that they will show similar changes. f(w) must depend on ice conditions, and F(v) must be related to the turbulence in the atmosphere over the ice.

III. Ice Resistance and Wind Action Calculated from the Observations

f(w) and F(v) can be calculated by using the wind and drift observations published by Brennecke. Eqs. (6) and (7) then are written

$$\left.\begin{aligned} f(w) &= \frac{D\omega\sin\varphi}{\pi}\cdot\frac{1 - \mathrm{tg}\,\alpha}{\mathrm{tg}\,\alpha} \\ F(v) &= \frac{D\omega\sin\varphi}{\pi}\cdot\frac{r}{\sin\alpha}. \end{aligned}\right\} \qquad (8)$$

The wind factor, r, and the deflection angle, α, are among the magnitudes on the right side of these equations that can be derived from the observations, but D, the depth of frictional resistance, cannot. It is generally assumed that the depth of friction resistance increases with increase in surface motion. However, Brennecke's observations are inadequate for proving this relationship. We shall, in what follows, introduce a hypothesis concerning this relationship, and then proceed to the final calculation of f(w) and F(v) on the basis of this hypothesis.

This calculation will not make direct use of the mean values published by Brennecke, because he disregarded certain individual values in computing the mean. He defined the mean wind factor as the arithmetic mean of individual wind factors, and the mean deflection angle as the mean of individual deflection angles. This definition suggests that some values could so greatly influence

the means that they could no longer be considered. However, such disregard, which always involves some arbitrariness, can be overlooked if the mean wind factor is defined as the relationship between the mean drift and wind speeds

$$r = \frac{\Sigma w}{\Sigma v}$$

and the mean deflection angle is calculated using the equation [6]

$$\operatorname{tg} \alpha = \frac{\Sigma vw \sin \alpha}{\Sigma vw \cos \alpha}$$

Table 1. Relationship Between Wind Speed and Ice Drift

	v, m/sec	0-2.9	3.0-4.9	5.0-6.9	> 6.9
Grouped by wind speed	$\bar{v}$, m/sec	1.91	3.91	5.87	8.74
	w, cm/sec	6.65	11.00	14.82	24.60
	α	36.2°	31.7°	29.0°	26.8°
	n	50	60	42	23
	w, cm/sec	0-5.9	6.0-11.9	12.0-17.9	> 17.9
Grouped by drift speed	$\bar{v}$, m/sec	1.94	3.62	5.01	7.69
	w, cm/sec	3.14	8.90	14.90	24.60
	α	40.2°	37.0°	24.9°	28.0°
	n	24	74	46	31
Mean	$\bar{v}$, m/sec	1.92	3.75	5.43	8.13
	w, cm/sec	5.52	9.81	14.86	24.60
	α	37.5°	34.9°	26.9°	27.5°
	$10^2\, \bar{r}$	2.88	2.62	2.74	3.03

Relationship between wind speed and drift. Study on the relationship between wind speed and drift must group the observations by wind speed, as well as by drift speed, because the individual values can be prone to errors. Data on drift speeds, for example, were generally rounded off to a whole number of nautical miles for a day's run (2.14 cm/sec). This was true in 135 of 174 cases. Only one regression line is obtained when observations containing errors are grouped according to one argument, as we know. Table 1 shows the mean values calculated. The upper entries are the results obtained by grouping according to wind speed, the middle entries are those derived from grouping by drift speed, and the lower entries are the means calculated from the figures for the first two groups. The results agree with those found by Brennecke. The wind factor appears to be independent of wind speed, but the deflection angle decreases with increase in wind speed. The mean values $10^2\, \bar{r} = 2.80$ and $\bar{\alpha} = 28.9°$ were obtained by using all observations. The mean wind factor concords well with the 2.78 value derived by Brennecke in another way, but our mean deflection angle is 5° smaller than Brennecke's (34°).

Eq. (8) can be used to calculate $f(w)$ by initially assuming that the depth of frictional resistance is constant. 50 m is used as the numerical value, and is from Brennecke's observations. Moreover, ω sine $\varphi = 0.68 \cdot 10^{-4}$, corresponding to a mean latitude of 69°. We find

wind speed, v, m/sec	1.92	3.75	5.43	8.13
drift speed, w, cm/sec	5.52	9.81	14.86	24.60
10^2 f(w)	3.3	4.7	10.5	9.9
10^3 f(w)/w	0.60	0.48	0.71	0.40

Note that the resistance function increases with increase in wind speed, and that $f(w)$ can be written approximately in the form $f(w) = a \cdot w$, where a is a constant. The tangential force attributable to ice resistance thus has the form $f(w) \cdot w = a \cdot w^2$; that is, ice resistance is approximately proportional to the square of drift speed. The author found that ice resistance is proportional to drift speed for ice drift on the Siberian continental shelf. The results cannot be compared, however, because the approach to the subject, as mentioned above, was entirely different, and the coefficient introduced had a different physical sense. Moreover, the ice cover on the Siberian shelf was entirely different in nature. The sea on the shelf was covered year 'round by an almost continuous ice layer about 3 m thick, whereas the ice cover in the Weddell Sea formed during the winter, and therefore did not even begin to approach the thickness found in Arçtic drift ice. Brennecke's observations also show that large polynyas were frequent in the Weddell Sea, even in midwinter. Given these circumstances, it is understandable that the ice has greater freedom of movement at low wind speeds, because the polynyas that are present often are not closed. Ice heads, showing great resistance in proportion to their kinetic energy, occur only at greater wind speeds.

It has been assumed up to this point that depth of frictional resistance is independent of the speed on the surface. This assumption, as already emphasized, does not concord with the general opinion on the subject because according to that opinion depth of frictional resistance increases with increase in surface speed. If we assume that ice resistance is in fact proportional to the square of the drift speed, and if we introduce the value $a = 0.54$, as the proportionality factor, we can calculate depth of frictional resistance and find

drift speed, w, cm/sec	5.52	9.81	14.85	24.60
depth of frictional resistance, D, m	45.6	55.2	39.1	69.1

These figures indicate an absolute increase in depth of frictional resistance with increase in drift speed, and the only divergence is at a speed of 15 cm/sec. Figure 2 is the corresponding graph. The value of $w = 15$ cm/sec was omitted in plotting the curve, which is considered to be a correct representation of the relationship between depth of frictional resistance and drift speed in what follows. The depth of frictional resistance values that must be introduced later to calculate $f(w)$ and $F(v)$ are taken from this curve. It is possible that the curve will provide values for depth of frictional resistance that are too high because the mean depth of frictional resistance becomes greater than the 50 m value given by Brennecke when the $w = 15$ cm/sec value is disregarded. This is not important, however, because we are interested primarily in changes in the functions, and not in their absolute values.

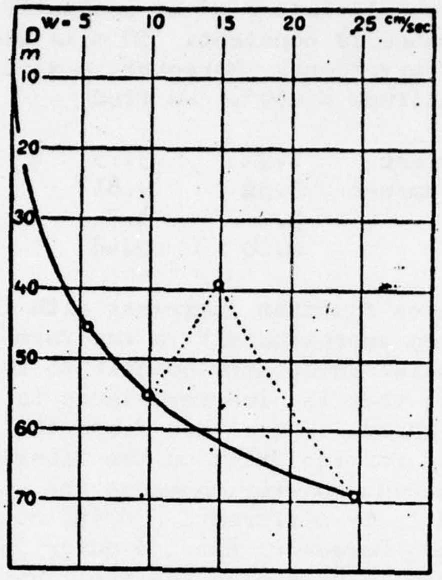

Figure 2. Relationship between surface speed and depth of frictional resistance, assuming that ice resistance is proportional to the square of the surface speed.

Let us now consider F(v). If we take the values for the depth of frictional resistance from the curve in Figure 2, we find

wind speed, v, m/sec	1.92	3.75	5.42	8.13
10^3 F(v)	4.7	5.5	7.5	9.5
10^4 F(v)/$\sqrt{v}$	3.4	2.8	3.2	3.3

The last line shows that F(v) can be written approximately in the form $F(v) = b \cdot \sqrt{v}$, where b is a constant. The tangential force of the wind then is in the form $b \cdot v^{3/2}$. It may have been anticipated that this tangential force was proportional to the kinetic energy of the wind; that is, proportional to the square of the wind speed. Were this the case, the depth of frictional resistance would increase much more rapidly with increase in surface speed, and ice resistance would increase more rapidly than the square of the drift speed. The latter in particular would appear to be highly unlikely. We know so little about energy transfer from atmosphere to ice that we cannot reject the relationship $F(v) = b \cdot v^{3/2}$ out of hand. Let us, therefore, summarize the above considerations as follows. If we assume that the relationship between depth of frictional resistance and surface speed can be represented by the curve in Figure 2, we can say that the mean relationship between wind speed and ice drift observed in the Weddell Sea can be explained by the fact that the tangential force of the wind is proportional to the 3/2 power of the wind speed and that ice resistance is proportional to the square of the drift speed.

Seasonal change in the relationship between wind and ice drift. The mean monthly wind factor and mean deflection angle, calculated using the above equations, are listed in Table 2. They deviate somewhat from those calculated

by Brennecke, but in the main are in agreement. Two means are listed for the first month, March, because the means for this month are very significantly influenced by the first single value. The means are in parentheses when this first value has been included.

Table 2. Monthly Means for Wind Speed, etc.

Month	$\bar{v}$, m/sec	$\bar{w}$, cm/sec	$10^2\ \bar{r}$	$\bar{\alpha}$, °	$10^3 a$	$10^4 b$
(Mar)	(5.17)	(16.5)	(3.20)	(23.3)	(10.9)	(4.9)
Mar	4.25	14.0	3.30	40.1	1.7	3.3
Apr	3.47	10.8	3.12	43.6	0.6	3.0
May	4.07	9.3	2.29	31.2	8.2	2.6
Jun	3.71	8.0	2.16	28.9	11.3	2.6
Jul	4.60	12.4	2.70	30.5	7.2	3.2
Aug	4.41	13.7	3.10	36.1	3.5	3.3
Sep	4.60	12.6	2.74	28.1	8.9	3.5
Oct	5.08	15.0	2.96	21.5	13.7	4.8
Nov	5.11	15.3	3.00	27.1	8.4	3.9

The seasonal changes in the wind factor and deflection angle are shown graphically in Figure 3. It is immediately apparent that there is a close relationship between the two magnitudes in the winter, April to September. This relationship can be explained by the theoretical consideration that the wind action remains almost unchanged during this period, whereas ice resistance is subject to great variations.

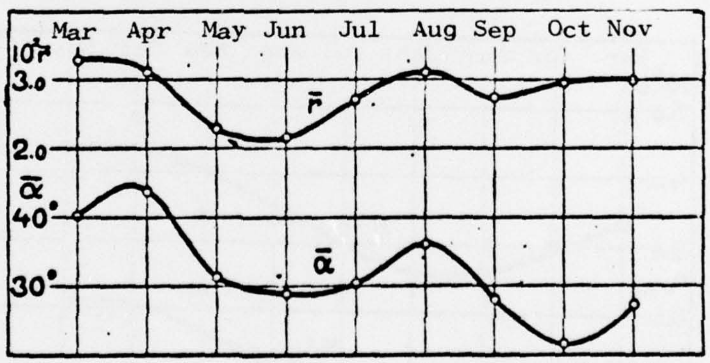

Figure 3. Seasonal change in wind factor and deflection angle.

The right side of Table 2 lists the coefficients of resistance, a, and wind action, b, introduced above. The resistance coefficient initially increases rapidly, decreases in July and August, then continues to increase and reaches its maximum in October. The increase during the first few months undoubtedly can be ascribed to the increase in ice cover, and to the effect of the onset of ice heads. The graph in Figure 4 also shows that ice resistance generally increases in the winter and spring. This is to be expected, and is in agreement with results from the Siberian shelf. The small July and August values are worthy of note. However, Brennecke, in his remarks, emphasizes

that large polynyas were particularly frequent in July and August. It seems justified, therefore, to ascribe the low resistance in these months to the presence of the many polynyas.

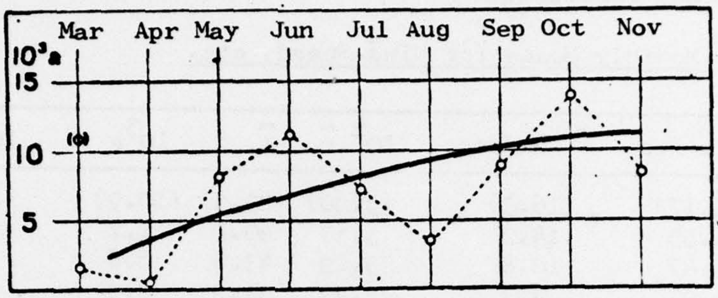

Figure 4. Seasonal change in the ice resistance coefficient.

The wind action coefficient, b, is much more regular, with minimum values in the middle of the winter, and an almost steady increase during the later part of the winter and spring. This change matches that for the Siberian shelf. There, the change in wind action during the winter was ascribed to a parallel change in turbulence in the bottom layers of the atmosphere, which, in turn, is associated with the fact that air cools from the bottom up in the winter, making the layering over the ice a very stable one, while convection currents begin in the spring, when the sun rises higher and higher over the horizon, resulting in a great increase in turbulence. Correspondingly, the increase in wind with height showed a change parallel to the wind action in the winter.

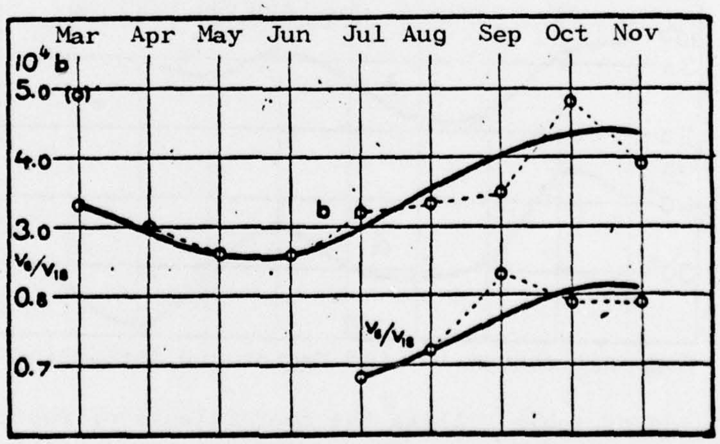

Figure 5. Seasonal change in the wind action coefficient, and increase in wind with height.

Measurements of wind speed at two heights, 6 and 18 m above the ice, are found among the meteorological observations of the German Antarctic Expedition published by E. Barkov [7]. The ratio of wind speed at 6 m to wind speed at 18 m can be taken as a standard of turbulence. The speed increases

rapidly with increase in height if the ratio is small. However, when turbulence is weak, we can expect that the transfer of kinetic energy to the ice is small relative to wind speed at 6 m; that is, the wind action is weak, and vice versa. Unfortunately, the measurements of wind speeds at the two heights do not cover the entire period of time in question; only July to November. Figure 5 shows that the values for change in wind with height during these months are approximately parallel to the values of the wind action coefficient. Accordingly, here too, seasonal changes in wind action could be ascribed to a parallel change in turbulence in the bottom layer of the atmosphere.

Let us emphasize at this point that the characteristic traits of the seasonal changes in ice resistance and wind action are almost independent of the assumptions concerning the form of f(w) and F(v). The functions would have shown the same changes had they been calculated assuming a constant depth of frictional resistance, and the physical interpretation would have been the same. However, it also must be emphasized that coefficients a and b, calculated on the basis of a variable depth of frictional resistance are subject to more regular and clearer changes, and thus real significance must be ascribed to these coefficients.

Relationship between wind and ice drift under quasi-stationary conditions. Finally, let us see if we can demonstrate a relationship between wind factor and deflection angle under quasi-stationary conditions, and if this relationship can be ascribed to changes in ice resistance. For this purpose, we look for periods during which wind direction and wind speed were approximately constant. Barkow's work contains a weather survey with notations about changes in wind speed and wind shifts. The data show that the changes were small in the periods listed below. The dates on which the periods ended were March 26, 31; April 13, 15, 16; May 14, 25; June 8, 9, 10, 25, 26; July 6, 7, 25, 28; August 8, 9, 13, 14, 15, 19. Only the months of March to August, during which the wind action coefficient was almost constant, were considered.

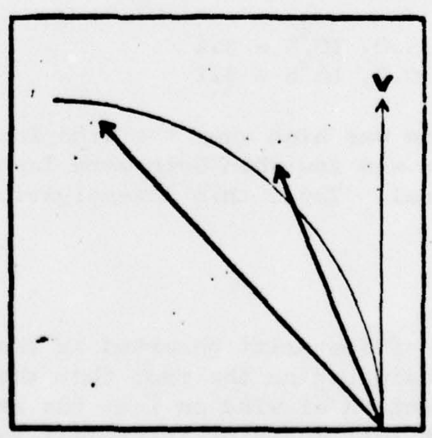

Figure 6. Observed relationship between wind and ice drift with constant wind action and increase in ice resistance.

The observations from the above periods were first broken down into two groups, depending on whether the wind factor was greater or smaller than the mean value (2.80), then again into two groups, depending on whether the deflection angle was greater or smaller than the mean value (29), and the means were calculated for each group. The results are listed in Table 3. Note that each group yields a relationship between the wind factor and deflection angle, both are either great or small. The relationship also is expressed by the fact that the correlation factor between wind factor and the sine of the deflection angle has a value of 0.5. The means listed at the bottom of the

Table 3. Relationship Between Wind and Ice Drift Under Quasi-Stationary Conditions

		n	$\bar{v}$, m/sec	$\bar{w}$, cm/sec	$10^2\ \bar{r}$	$\bar{\alpha}$, °
Grouped by r	Group I	13	5.50	12.6	2.29	24.8
	Group II	9	4.76	16.5	3.46	38.4
Grouped by α	Group I	12	5.62	13.3	2.37	18.5
	Group II	10	4.59	15.2	3.32	46.7
Means	Group I	-	5.55	12.9	2.32	21.8
	Group II	-	4.67	15.8	3.39	42.8

table were obtained by combining the values for the two groups. These values are illustrated graphically in Figure 6. A comparison of these values with Figure 1 shows that the relationship between wind factor and deflection angle under quasi-stationary conditions is in good agreement with the relationship derived theoretically.

We calculated the following from the means

Group I $10^3 a = 15.0$, $10^4 b = 3.4$
Group II $10^3 a = 0.7$, $10^4 b = 3.1$

and found that ice resistance was high when the wind factor and deflection angle were small; resistance was low when both were large. Wind action within the groups is almost identical. Thus, this investigation too confirms our considerations.

IV. *Summary*

The principal features of ice drift observed in the Weddell Sea can be explained by taking into consideration the fact that the ice drift depends on the following factors: the action of wind on ice; the resistance that is produced when ice collides with ice; depth of frictional resistance; and the deflecting force of the earth's rotation.

The premise leads to the fact that the relationship between depth of frictional resistance and surface speed can be illustrated by the curve shown in Figure 1, that the tangential force of the wind can be in the form $b \cdot v^{3/2}$, where coefficient b depends on the turbulence in the bottom layer of the atmosphere, and therefore shows an annual periodicity. Ice resistance can be written as $a \cdot w^2$, where coefficient a depends on ice conditions; the coefficient is small when the ice is thin, or when many polynyas are present; the coefficient is large when the ice is thick and densely packed.

Changes in wind action and ice resistance correspond to those demonstrated for the Siberian continental shelf. However, a direct comparison with ice drift on the shelf is not permissible because hydrographic conditions are different on the shelf.

The wind factor over the Weddell Sea is greater than over open oceans. This can be attributed to the fact that ice presents a better attacking surface to wind than does the open sea. On the other hand, the fact that the wind factor over the Arctic Ocean is smaller than over the Weddell Sea must be associated with the fact that Arctic ice offers greater resistance to motion than ice in the Weddell Sea.

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